

EFFECT OF MUNICIPAL TREATED WASTEWATER AND BRACKISH GROUNDWATER
ON THE WATER HOLDING PROPERTIES OF A CLAYEY, CALCAREOUS SOIL

A Thesis

by

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ABSTRACT

Wastewater reuse is a practice that has been gaining attention for the past few decades as the world's population rises and water resources become scarce. This study compared the long-term (15+ years) effects and suitability of using secondary-level treated municipal wastewater and brackish groundwater for irrigation on the water holding capacity of a clayey, calcareous soil on a cotton farm near San Angelo, Texas. The soil-water holding properties were determined from the extracted hydrostructural parameters of the two characteristic curves: water retention curve and soil shrinkage curve based on the pedostructure concept. In the pedostructure concept, these hydrostructural parameters are characteristic parameters of the soil aggregates structure and its thermodynamic interactions with water. Results indicate that use of secondary treated wastewater increased available water capacity in the top horizon (0-15 cm) and decreased the available water holding capacity of this particular soil in the sub-horizons (15-72 cm). The brackish groundwater irrigation resulted in no effect on available water capacity in the top horizon, but significantly decreased it in the sub-horizons as well. The rainfed soil was the healthiest soil in terms of water holding capacity, but rainfall conditions do not produce profitable cotton yields due to insufficient water. Whereas, treated wastewater irrigated soil is producing the highest yields for the farmer. Thus, this treated wastewater source and irrigation system can serve as a suitable irrigation alternative to using brackish groundwater, enhancing the water resource sustainability of this region.

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1. INTRODUCTION AND LITERATURE REVIEW

Background

The future holds many challenges for humanity and its relationship with natural resources, considering population growth, climate change, and the resulting resource competition. Water and food are critical resources for human survival, and soil is at the nexus between human consumption and production of these two resources. Ensuring the environmental, economic, and social sustainability of these resources will require creative, diligent, and localized solutions. West Texas is a semi-arid and sub-tropical region that experiences competition for water between the energy, agriculture, and municipal sectors. In the state of Texas, it is predicted that there will be a 38% water gap by 2050 (2017 Texas State Water Plan), and this plan recommends that reuse makes up for 14.2% of recommended water management strategies to overcome this gap. Treated wastewater (TWW) from municipal wastewater treatment plants has the potential to provide a significant amount of irrigation water for commercial row-crop agriculture, and this is a practice already being employed in the Texas and elsewhere (Arroyo et al., 2011). Brackish groundwater is also an alternative irrigation water source available in west Texas and other regions, which farmers are applying to their soil and crops (George et al., 2017). The environmental and human health impacts of applying different qualities of irrigation water must be evaluated, and because soil is at the nexus of water and food security, the impacts of such practices on soil should be fully understood. Soil is a dynamic and complex medium, and different soil types will react differently to different water qualities. Thus, farmers and decision-makers should understand the implications of alternative irrigation water application with regard to water management and irrigation scheduling.

Previous Research

Treated Wastewater Use

There are many examples of treated wastewater reuse in agriculture over the past few decades from around the world, especially in arid, semi-arid, and subtropical climates such as those found in the Middle East and in Mediterranean countries (Pedrero et al., 2010).

There has been an abundance of research looking at the effects on soil properties of using secondary-level municipal TWW for agriculture irrigation. The following literature review cites studies which utilized water of this treatment level. Typical secondary level municipal wastewater treatment involves physical treatment by large filters and settling basins, biological treatment to decrease organic content in the water, and some sort of disinfection. In Texas, the quality criteria for agricultural water reuse from municipal treatment plants is focused on human health concerns related to pathogens and microbes. The designation for secondary treated wastewater to be reused for irrigation of non-food crops is termed “Type II” reclaimed water, which has the following quality thresholds by the Texas Commission of Environmental Quality (TCEQ, 2017) (Texas Administrative Code, Rule 210.33) (Table 1).

Table 1: Type II water quality parameters and limits (Texas Commission on Environmental Quality, 2017) (Reprinted from Texas Administrative Code, Rule 210.33).

Parameter	Limit
BOD 5	20 mg/l
CBOD 5	15 mg/l
Fecal coliform or E. coli	200 CFU/100 ml *
Fecal coliform or E. coli	800 CFU /100 ml **
Enterococci	35 CFU/100 ml *
Enterococci	89 CFU/100 ml **

*30 day geometric mean, **max. single grab sample

Impact on Soil Properties

Much of the previous research shows that TWW irrigation causes an increase in soil salinity as indicated by electrical conductivity (EC) and/or total dissolved salts (TDS) (Qian and Meham, 2005; Rusan et al., 2007; Tarchouna et al., 2010; Xu et al., 2010; Assouline and Narkis, 2013; Bedbabis et al., 2014; Hidri et al., 2014; Levy et al., 2014; Schacht et al., 2014; Abunada et al., 2015; Tunc and Sahin, 2015; Adrover et al., 2016; Gharaibeh et al., 2016). TWW irrigation has also been found to increase sodicity of a soil, indicated by the sodium adsorption ratio (SAR) (Qian and Meham, 2005; Levy et al., 2014). However, TWW irrigation has also been found to have no effect on clay soils' sodium levels (Heidarpour et al., 2007; Bardhan et al., 2016) or to cause a reduction in soil salinity with an increase in sodicity in naturally salt-rich soils in a semi-arid region of Brazil (Carlos et al., 2016). The discrepancy of results regarding salinity and sodicity indicates that the type of soil and its unique characteristics (like texture, parent material, mineralogy, etc.) play a role in its reaction to TWW irrigation. For example, in the case of Carlos et al. (2016), TWW irrigation in naturally salt-rich soils caused a decrease in salinity due to leaching since the TWW was relatively lower in salt content than the existing soil-water matrix.

An important parameter regarding soil-plant health is pH because pH can affect nutrient charge and thus increase or decrease their availability to plants as well as the activity of microorganisms in a soil and pollutant mobility in the soil (Brady and Weil, 2008; Urbano et al., 2017). A soil's pH is a result of the combined effects of soil-forming factors (parent material, time, relief, climate, and organisms) and human activities ("Soil pH", USDA-NRCS). For example, humid regions tend to have soils with a lower pH because acidification occurs at higher rates when rainfall is sufficient to leach the profile (Brady and Weil, 2008). Conversely, leaching

is less extensive in drier regions, allowing the soils to retain cations like Ca^{2+} , Mg^{2+} and Na^+ , which prevent the buildup of acid cations, resulting in more alkaline pH levels in the soils. Additionally, soils high in clay and organic matter tend to be more capable of buffering changes in pH than sandy soils because high infiltration rates in sandy soils makes them more susceptible to acidification (“Soil pH”, USDA-NRCS). Studies that looked at the impact of TWW irrigation on soil pH do not unanimously concur. TWW irrigation can cause a lowered pH (Xu et al., 2010; Bedbabis et al., 2014; Abunada et al., 2015), which could be due to oxidation of organic compounds and/or the nitrification of ammonium (Mohamed and Mazahreh, 2003; Rosabal et al., 2007). TWW irrigation can also cause an increased pH (Qian and Mecham, 2005; Vogeler, 2009; Tarchouna et al., 2010; Carlos et al., 2016; Irandoust and Tabriz, 2017), which could be due to increase of cations like Na^+ , Ca^{2+} , and Mg^{2+} with TWW irrigation. Lastly, TWW also can have no effect on soil pH (Hidri et al., 2014; Bardhan et al., 2016), due to the buffering capacity of calcareous and clayey soils. As was the case for salinity and sodicity, this lack of concurrence in effect on pH can be attributed to the testing of different soil types, textures, conditions, and parent materials in the different studies, but none of the previous research found a pH change in the soils due to TWW irrigation to be agronomically limiting.

Numerous other studies looked at relevant soil chemical properties such as organic matter, total carbon, total nitrogen, and the presence of plant nutrients and micro-nutrients like potassium, phosphorus sodium, magnesium, and boron. TWW irrigation has caused an increased organic matter (Rusan et al., 2007; Xu et al., 2010; Bedbabis et al., 2014; Abunada et al., 2015; Gharaibeh et al., 2016;), increased carbon, as indicated by total carbon (Xu et al., 2010; Vogeler, 2009) and organic carbon (Tunc and Sahin, 2015), increased total nitrogen (Xu et al., 2010) or N-NO_3 (Adrover et al., 2016), and increased plant nutrients (Rusan et al., 2007; Tarchouna et al.,

2010; Urbano et al., 2017). TWW irrigation can also cause an increase in potassium (Heidarpour et al., 2007; Truu et al., 2008; Urbano et al., 2017) and phosphorus (Qian and Mecham, 2005). However, Heidarpour et al. (2007) also found no significant effect of TWW irrigation on phosphorus and total nitrogen, perhaps due to plant uptake, and two other studies found a reduction in total nitrogen (Carlos et al., 2016; Irandoust and Tabriz, 2017). Also, the effect of TWW irrigation on these chemical parameters has been found to be the most significant in the top soil layers (0 to 15 cm depth) (Heidarpour et al., 2007; Xu et al., 2010).

Also important to soil health, soil functionality, and human health are microbiological characteristics of a soil-water environment. Biochemical Oxygen Demand (BOD) and Total Suspended Solids (TSS) are commonly reported water quality parameters that can give some indication about the presence of microbes in the water. The United States Environmental Protection Agency (EPA, 2012) recommends that BOD and TSS levels remain below 30 mg L⁻¹ to be safe for treated wastewater irrigation to avoid soil clogging, absorption by plants, and adverse human health impacts. These characteristics also include presence of fecal coliforms and harmful bacteria, where microbial mass can serve as an indicator of microbial activity. TWW irrigation has a tremendous effect on soil microbiology. Irrigating with TWW can cause an increase in soil's *E. coli*, enterococci, and sulfite-reducing *Clostridium* spores, but not salmonella (Palese et al., 2009). TWW irrigation can also increase in levels of fecal coliform and soil microbial biomass (Hidri et al., 2014) and in microbiological activity (Truu et al., 2008), especially in clayey soils (Hentati et al., 2014). However, while TWW irrigation can increase fecal coliform levels in the soil, the increase is typically not high enough to be deemed biologically contaminated (Abunada et al., 2015). TWW irrigation can also have no effect on *E. coli* bacteria in the soil or plant (Sklarz et al., 2014; Urbano et al., 2017). Lastly, soil type has

been found to have more effect on soil biological activity than irrigation water type for multiple soil types (Adrover et al., 2017).

TWW irrigation not only has an effect on soil chemical and physical properties, but also on the plants growing in the soil. The study site for this research is a cotton farm that has been irrigated with TWW for over 15 years. TWW irrigation has been found to cause a significant increase in yield (bolls/m²), leaf area index, and plant height for cotton plants with no detrimental effect on cotton fiber quality (Alikhasi et al., 2012). Other research has focused on the effects of TWW irrigation on other plants, with both positive and negative results. With barley, the plant biomass increased with added TWW and associated nutrients after 2 and 5-yr periods; however, a longer 10-yr period of TWW application resulted in lower biomass production than the shorter periods of irrigation but remained higher than that of control plants (Rusan et al., 2007). With alfalfa, metal uptake into the plant was measured, but the amount was within the acceptable range, according to Food and Agriculture Organization (FAO) standards (Abunada et al., 2015). TWW irrigation has been found to challenge and damage the root system in both a sandy loam and a clay, leading to large reductions in root growth and increased salt uptake, membrane leaking, proline content, decreased root viability, carbohydrate content, and osmotic potentials in the fine roots. The effects were more pronounced in the clay soil. Lastly, the TWW irrigation influences diameter, specific root area, tissue density, and cortex area only in clay soil and can severely reduce root hydraulic conductivity in the clay soil (Paudel et al., 2016).

Coppola et al. (2004) make a case that soil physical and hydrologic characteristics should be considered to define appropriate guidelines for wastewater management, not just chemical and biological. Previous research most relevant to our work includes investigations of soil

hydraulic properties including saturated hydraulic conductivity (K_s), infiltration rate, bulk density, porosity, clogging of soil pores, cumulative flow, and water retention.

Tarchitzky et al. (1999) showed that an important effect of adding organic matters (OM) to soil from TWW irrigation is the increase of moisture retention capacity, due to the reduction of soil bulk density and specific surface area of soil particles. However, a recent study sought to quantify the widely promoted notion that increased organic matter increases soil water retention by looking at the USDA-NRCS soil characterization database (Minasny et. al., 2017). They found that the effect of adding OM to soil does enhance available water capacity, but only modestly. Sandy soils are known to be most responsive to this effect; whereas the effect of OM on water retention in clayey soils was found to be almost negligible. Additionally, Tarchitzky et al. (1999) conclude that dissolved humic substances increases clay dispersion, which makes a case that an increase in sodicity may not be the only driving factor in decreased infiltration rates from TWW irrigation. Three pore space-types have been defined in the soil volume, which were considered: macropore space, which is considered to control aeration and drainage, mesopore space, which is considered to control conductivity, and micropore spaces which is considered to control water retention and available water for plants (Luxmoore, 1981). Luxmoore (1981) defines the micro-, meso-, and macropores in terms of retention and pore diameter ranges. However, it is important to note at this time that this paper will utilize the Pedostructure Concept and Hydrostructural Pedology (Braudeau et. al., 2004; Assi et. al., 2014; Assi et. al., 2017) to define the micro- and macropore spaces as well as available water capacity – these definitions are presented in the methods section.

The general consensus of preceding research, reported in this paragraph, is that TWW irrigation causes a degradation of the soil hydraulic properties. Exceptions to this degradation

occur, depending on soil properties like texture. TWW irrigation decreases soil saturated hydraulic conductivity (K_s) across different soil types and textures (Viviani and Iovino, 2004; Abedi-Koupai et al., 2006; Gonçalves et al., 2007; Sepaskhah and Sokoot, 2010; Tarchouna et al., 2010; Assouline and Narkis, 2011; Assouline and Narkis, 2013; Balkhair, 2016; Bardhan et al., 2016; Bourazanis et al., 2016; Gharaibeh et al., 2016). Reduction of K_s was found to be more pronounced in clayey soils, as compared to sandier soils (Viviani and Iovino, 2004; Sepaskhah and Sokoot, 2010) and more pronounced in the upper layer of the soil (<20 cm) (Viviani and Iovino, 2004). Decreases in K_s are likely due to pore clogging of suspended solids in the TWW filling up soil voids (Viviani and Iovino, 2004; Tunc and Sahin, 2015; Gharaibeh et al., 2016;), and a reduced K_s indicates that TWW irrigation affects structural porosity via reducing the macro- and mesopores of the soil structure (Bardhan et al., 2016). The issue of pore clogging and decreased soil K_s could be solved by applying water filtration before irrigation with TWW (Urbano et al., 2017). Further, there is a positive correlation between hydraulic conductivity and both EC and CaCO_3 and a negative correlation between hydraulic conductivity and both SAR and ESP (Bourazanis et al., 2016). A few exceptions were found in the literature to a decrease of K_s : TWW irrigation caused an increased K_s in a silt loam (Vogeler, 2009) and an increased hydraulic conductivity at lower water contents, indicating a change in the soil structure and its microporosity (Gonçalves et al., 2007). TWW irrigation caused no change in K_s of a clay oxisol soil (Urbano et al., 2017).

Hydraulic conductivity is highly related to infiltration rates and cumulative flow through the soil medium. TWW irrigation can cause a decrease in infiltration rates or cumulative flow (Assouline and Narkis, 2011; Tunc and Sahin, 2015; Balkhair, 2016; Gharaibeh et al., 2016).

However, with sprinkler irrigation TWW irrigation can cause an increased infiltration rate with clays, a silty clay, and a silty clay loam using sprinkler irrigation (Abedi-Koupai et al., 2006).

TWW irrigation can have a positive or negative effect on soil moisture and water holding capacity parameters. TWW irrigation has been found to increase soil moisture (Hentati et al., 2014; Tunc and Sahin, 2015). For a loamy soil, TWW irrigation caused an increased field capacity, permanent wilting point, and overall available water capacity, due to an increased micropore volume (pressure plate method) (Tunc and Sahin, 2015). Similarly, TWW irrigation caused an increased water retention (as a function of infiltration by using HYDRUS-1-D) in lower layers of a clay (59% content) due to a decreased mean pore radius, but TWW irrigation also caused a decreased water retention capacity for this clay in the top layer of the soil due to an increased mean pore radius (Assouline and Narkis, 2011). A similar decrease in water retention from TWW irrigation was observed in a sandy clay loam (~20% clay) in a disturbed top layer of the horizon, attributed also to a narrowing of pore space (Coppola et al., 2004).

Hydrophobicity is a characteristic that is thought to be caused by organic compounds accumulating in the soil and is associated with reduction in water infiltration rates and increased surface runoff. Sandy textured soils have a higher propensity to hydrophobicity because they have smaller surface areas than clays and silts, which allows for more extensive coating of the particles (Encyclopedia of Soil Science, 2008). TWW irrigation causes a soil's hydrophobicity to increase (Arye et al., 2011) (Vogeler, 2009).

Bulk density and porosity are both related to soil structure and are indicators of space in the soil in which water can be stored and transported. TWW irrigation can cause an increased bulk density (Abedi-Koupai et al., 2006; Tunc and Sahin, 2015) due to dispersion and sedimentation of clay particles (Abedi-Koupai et al., 2006). TWW irrigation can also cause a

decreased bulk density in silt loams (Vogeler, 2009). Relatedly, TWW irrigation can increase in overall porosity (Vogeler, 2009; Tunc and Sahin, 2015) or a decreased porosity (Coppola et. al., 2004; Abedi-Koupai et al., 2006). One example of TWW irrigation resulted in a decreased macro-porosity with an overall increased porosity (Vogeler, 2009). Lastly, TWW irrigation has been found to enhance soil's aggregate stability, which would indicate that reduced K_s and infiltration is due to pore clogging and not dispersion (Vogeler, 2009; Tunc and Sahin, 2015; Gharaibeh et al., 2016).

Impact on Soil-Water Management and Irrigation

The water retention capacity of a soil should play a significant role in a farmer's irrigation management. Irrigation efficiency is an especially important consideration in arid and semi-arid regions which face competition for water resources among different sectors, especially considering that less than 65% of applied water is actually being utilized by crops (over irrigation) (Chartzoulakis and Bertaki, 2015). The most efficient irrigation scheduling technique is a water balance approach, which calculates a net irrigation requirement as the amount of water required to fill the root zone soil water back to field capacity. This calculation should account for evapotranspiration, precipitation, infiltration, upflux of shallow groundwater, and deep percolation (Andales et. al., 2015). In Saudi Arabia, TWW irrigation has been found to reduce soil's overall irrigation water use efficiency, calculated as total yield per hectare for the season divided by total water supply per hectare. This reduction was theorized to be due to the capacity of the clays to attract TWW constituents by mechanical processes such as sorption-adsorption, attachment-detachment, and cation exchange (Balkhair, 2016).

Hypotheses and Objectives

Because the literature does not provide conclusive or consistent evidence that TWW degrades soil quality, particularly with regard to water holding properties, the authors of this research have reason to believe that the unique soil properties (texture, parent material, climate, etc.) of each case study, in combination with irrigation water qualities, play a highly significant role in determining the impact of TWW irrigation for each case. However, many sources stand to claim that TWW irrigation degrades soil hydraulic and water holding properties, so this study sought to test the hypothesis that irrigating with TWW is not a suitable alternative to the brackish groundwater source in San Angelo, Texas by way of degrading the soil's water holding ability. The reason for such a degradation could be attributed to multiple working hypotheses which have arisen from the literature: (1) reduction of pore space by clogging of suspended solids/organic matter build-up in the soil, and (2) dispersion of the clay particles resulting from an increase in salinity or an addition of humic substances from increased organic matter. Because these soils are very high in clay content, both of these possibilities will be considered as hypotheses.

Thus, the objectives of this study are to (1) quantify the impacts of treated wastewater and groundwater irrigation on the soil water holding properties (e.g. water content at saturation, field capacity, permanent wilting point, and available water capacity) of a clayey, calcareous soil and (2) evaluate the long-term impact of irrigating with treated wastewater on irrigation management and overall water use in this region.

2. MATERIALS AND METHODS

Site Information

The sampling site was a cotton farm in San Angelo, TX (Tom Green County), a portion of which has been irrigated with TWW from the San Angelo Wastewater Treatment Plant for over 15 years. This farm has 365 acres (150 hectares) of land with drip tape irrigation, which was installed 12-14 inches (30-35 cm) deep in the soil; 250 acres (100 hectares) are irrigated with TWW, and the rest is irrigated with brackish groundwater. Additionally, this farm has 80 acres (32 hectares) of land left for dryland/rainfed agriculture. The farmer applies tillage by ripping in between the drip-tape at a 12-14 inch depth (30-35 cm) before planting. He also turns the top soil by a disk harrow at 6-8 in (15-20 cm) depth before planting cotton seeds with a John Deere Max Emerge planter. Annually, this region receives an average of 20.45 in. (519 mm) of rainfall with average temperature of 78°F (25°C) during the growing season (May through October), which means this area falls under a Humid Sub-Tropical (Cfa) climate region of Texas.

Soil and Water Sample Collection and Preparation

The soil at the sampling locations is the Angelo soil series, a fine-silty, mixed, superactive, thermic Aridic Calcicustoll. Angelo soil is formed in calcareous loamy and clayey alluvium derived from limestone (USDA, 2017). Three replicates of the first three horizons (A_p [0-15 cm], A [15-30 cm], and B [30-72 cm]) were sampled from seven locations (two locations from each experimental group plus a filter flush site, which was sampled only from the top horizon). The experimental groups are defined as: rain-fed (RF) as the control, TWW irrigated, Filter Flush (FF) irrigated, and brackish groundwater (GW) irrigated. “Filter flush” irrigation water comes from a back-flush mechanism of an on-site TWW disk filter (filter apparatus explained in the next section). The locations and date for each soil and water sample group is

recorded in Table 2 (TWW and groundwater source described in the next section). The location of each location can be seen from the USDA Web Soil Survey in Figure 1. Stars indicate each sampling location. The distances between the samples are also indicated by a 900 ft. (274 m) scale.

Table 2: Locations and dates of each soil and water sampling

Experimental Group	Location	Date Taken	Condition
Soil - RF1	31°25'53.4468"N, 100°23'7.08"W	15-Jun-17	Post Sow
Soil - RF2	31°25'54.4357"N, 100°22'53.0054"W	12-Oct-17	Pre-harvest
Soil - TWW1	31°25'41.9"N, 100°21'15.8"W	27-Mar-17	Pre-Sow
Soil - TWW2	31°25'31.1556"N, 100°22'46.5204"W	12-Oct-17	Pre-harvest
Soil - FF	31°25'19.4"N 100°22'37.9"W	27-Mar-17	Pre-Sow
Soil - GW1	31°25'51.4488"N, 100°23'7.71"W	15-Jun-17	Post Sow
Soil - GW2	31°25'51.2544"N, 100°22'52.9284"W	12-Oct-17	Pre-harvest
Water - TWW	31°25'41.9"N, 100°21'15.8"W	27-Mar-17	Canal
Water - GW	31° 25' 40.2816" N, 100° 22' 52.9896" W	12-Oct-17	120m Depth Well



Figure 1: Locations of soil samples in San Angelo, Texas.

Characteristics of Treated Wastewater and Groundwater Used for Irrigation

Many treatment options and applications exist for the reuse of municipal wastewater. This study is looking at the use of secondary-level municipal treated wastewater for irrigation from the San Angelo, Texas Wastewater Treatment Plant. This plant uses conventional activated sludge treatment for 9-10 million gallons (34-38 million liters) per day, with three anaerobic digesters to stabilize the sludge. The treatment process is as follows: (1) lift station to pump wastewater into the head works, (2) mechanical bar screens to remove large debris, (3) grit removal, (4) primary clarifiers for particle settling, (5) aeration for biological treatment to remove organic matter/pollutants, and (6) final clarifiers for sludge settling (“Water Reclamation”). With sufficient monitoring and maintenance this level of treatment (called “Type II” water by the TCEQ) is considered safe to discharge into the environment (usually into rivers). After leaving the treatment plant, the water is discharged into canals from which the farmers draw for irrigation, and the farm of study ran TWW through a disk filter. The filter (Figure 2), utilizes polypropylene disk filtration technology to capture suspended solids. The filter is periodically back-flushed out onto nearby soil (FF soil samples) (Arkal Spin Klin User Manual, 2011). The farmer uses the filter system to protect the drip tape irrigation system.



Figure 2: Treated wastewater disc filtration system: Amiad Arkal Spin Klin Filter. Filter has 120 mesh and 130 micron disc size.

The basic chemical characteristics of treated water from the San Angelo Wastewater Treatment Plant, are shown in Table 3. The limitation categories were assigned based on agriculture use under normal management conditions, as defined by a standard document provided by the Texas A&M Agrilife Extension service (SCS-2002-10). The Type II wastewater has high conductivity and total dissolved solids and slightly high levels of sodium, chloride, and nitrate. According to a report from the water quality laboratory in the San Angelo Wastewater Treatment Plant, the biochemical oxygen demand of the final effluent from the plant is around 20 mg L⁻¹.

The brackish groundwater used for irrigation was drawn from a 130 ft. (40 m) depth from the limestone Lipan Aquifer, a part of the Choza formation, which consists of saturated sediments of gravel and conglomerates cemented with sandy limestone and layers of clay

(George et al., 2011). The basic chemical characteristics of this water can be found in Table 3. The groundwater is high in calcium, magnesium, sodium, sulfate, chloride, nitrate, conductivity, and total dissolved solids. The farmers in this region prefer to use the treated wastewater over the brackish groundwater, as it produces better yields, is less hard, and is less saline.

Table 3: Characteristics the treated wastewater and groundwater used for irrigation. Data were provided in a water analysis report by the Texas A&M Agrilife Extension Soil, Water and Forage Testing Laboratory (2017).

Parameter Analyzed	Treated Wastewater	Groundwater	Units	Agricultural Use Category
Calcium (Ca)	101	739	Parts per million (ppm)	Acceptable
Magnesium (Mg)	49	200	ppm	Limiting - Acceptable
Sodium (Na)	229	495	ppm	Acceptable
Potassium (K)	25	8	ppm	Acceptable
Boron (B)	0.49	0.365	ppm	Acceptable
Bicarbonate (HCO ₃)	295	215	ppm	Acceptable
Sulfate (SO ₄)	212	1280	ppm	Acceptable
Chloride (Cl)	431.5	1339	ppm	Limiting
Nitrate (NO ₃ -N)	11.06	34.61	ppm	Limiting - Acceptable
Phosphorus (P)	2.5	0.07	ppm	Acceptable
pH	7.7	7.09		Acceptable
Electrolytic Conductivity (EC)	2.14	7.02	dS m ⁻¹	Very Limiting - Limiting
Hardness	454.5	2671	ppm CaCO ₃	Limiting - Acceptable
Alkalinity	241.5	177	ppm CaCO ₃	Acceptable
Total Dissolved Solids (TDS)	1357	4312	ppm CaCO ₃	Very Limiting - Limiting
Sodium Adsorption Ratio (SAR)	4.7	4.2		Acceptable

Theoretical Background for the Analysis of Water Holding Properties

This study looked at soil-water properties as applied by the Pedostructure Concept for hydrostructural (interaction between soil water and soil structure (Braudeau et. al., 2004)) characterization. The pedostructure concept was first introduced by Braudeau et al. (2004), and

the concept is built upon the pedological description of the soil aggregates, as defined by Brewer (1964). According to Brewer (1964), the soil structure is a hierarchy of structure levels composed of specific units of organization (soil aggregates or “pedostructure”) such as the s-matrix (material within primary peds), skeleton grains, plasma, and voids. Therefore, the assembly of primary peds, defined as the basic unit of pedality description and representing the first partitioning level of the clayey plasma, constitutes the pedostructure (Braudeau et al., 2004). Each soil type has a unique organization of pedostructure. Braudeau et al. (2004) presented the Pedostructure Concept as a quantitative definition of Brewer's description by considering the soil shrinkage curve, which is a good measure for the aggregate structure. The shrinkage curve was used to define two pore systems within an assumed structured soil medium: micro-pore and macro-pore, where the micro-pore space is within the primary peds (intrapedal), and the macro-pore space is outside the primary peds (interpedal). Braudeau and Mohtar (2004) also demonstrated a link between the pedostructure concept and the tensiometric water retention curve. Braudeau and Mohtar (2009) built upon this concept to introduce a new approach for modelling soil-water based on the Pedostructure Concept and the Structural Representative Elementary Volume (SREV) to take into account the aforementioned hierarchical organization of the soil structure. In this paper, the pedostructure is presented as the SREV of the soil medium, which allows for the thermodynamic characterization of the soil medium with respect to soil-water content. SREV accounts for soil's basic internal organization as a nonrigid structure composed of solid particles surrounded by changing amounts of water and air, but not structural mass and serves as a reference for the new equations (as opposed to volume, which serves as the reference variable for the Representative Elementary Volume). The SREV approach allows for thermodynamic and hydrodynamic characterization of the soil structure as well as ensuring a

physically-based (opposed to empirically based) modeling of soil water processes, which can be transferred from the physical scale to an application scale.

Subsequently, Braudeau et al., (2014a) and Assi et al. (2014) built upon the pedostructure concept to develop physical equations for the Soil Shrinkage Curve (ShC: relationship between specific volume and the gravimetric water content) and Water Retention Curve (WRC: relationship between soil matric potential and gravimetric water content). Braudeau et al. (2014a) and Assi et al. (2014) thermodynamically linked concepts of traditional pedology and soil-water physics, termed hydrostructural characterization and modeling of the soil medium. The hydrostructural characterization paradigm was based on the pedostructure concept, SREV, and the Gibbs thermodynamic potential function. Additionally, this method of hydrostructural characterization provides a thermodynamic formulation for micro- and macropore waters for the WRC, as defined by Braudeau et al. (2004) in the ShC. Under this method of hydrostructural characterization, the micro- and macropore spaces are not approximated by pressure or pore diameter ranges, as defined by Luxmoore (1981), but rather are unique to each soil and its structure. Assi et al., (2014) further demonstrated the hydrostructural characterization approach with the use of a new laboratory apparatus, called the TypoSoil™ (Bellier and Braudeau, 2013). Further, a complete framework and computer model for characterizing the internal soil organization and the soil's hydrostructural properties was presented by Braudeau and Mohtar (2014). Braudeau et al. (2014b) then thermodynamically unified the construction of the WRC from the measured points of the two different methods of getting the curve. The tensiometer can measure actual suction up to 1 bar (100 kPa), and the pressure plate measures air pressure inside the chamber up to 15- 20 bars (1500-2000 kPa). The parameters of the associated constructed WRC are the hydrostructural parameters, and the WRC

function makes a conversion of the air pressure applied in the pressure plate to be equal to soil suction.

Soil Characterization with TypoSoil™ Device and Analysis of Data

As mentioned, the hydrostructural properties of a soil are indicators of soil condition and function and play a dominant role in driving the soil-water interactions within the soil-plant-atmosphere continuum. Braudeau et al., (2014, 2016) applied the pedostructure concept to establish thermodynamic formulations of the two soil-water characteristic curves: water retention curve (WRC) and soil shrinkage curve (ShC), which are used in this study.

The equation of the pedostructure water retention curve (WRC) is

$$h^{eq}(W) = \left\{ \begin{array}{l} h_{mi}(W_{mi}^{eq}) = \rho_w \bar{E}_{mi} \left(\frac{1}{W_{mi}^{eq}} - \frac{1}{W_{miSat}} \right), \quad \text{inside the primary peds} \\ h_{ma}(W_{ma}^{eq}) = \rho_w \bar{E}_{ma} \left(\frac{1}{W_{ma}^{eq}} - \frac{1}{W_{maSat}} \right), \quad \text{outside the primary peds} \end{array} \right\}, \quad (1)$$

where, W is the pedostructure water content excluding the saturated interpedal water [kg_{water} kg_{soil}⁻¹], W_{ma} is gravimetric macropore water content "outside the primary peds" [kg_{water} kg_{soil}⁻¹], W_{mi} is gravimetric micropore water content "inside the primary peds" [kg_{water} kg_{soil}⁻¹], \bar{E}_{ma} is potential energy of surface charges positioned on the outer surface of the clay plasma of the primary peds [J kg_{solid}⁻¹], \bar{E}_{mi} is potential energy of surface charges positioned inside the clay plasma of the primary peds [J kg_{solid}⁻¹], h_{mi} is the soil suction inside the primary peds [dm ~ kPa], h_{ma} is the soil suction outside the primary peds [dm ~ kPa], ρ_w is the specific density of water [1 kg_{water} dm⁻³].

The equations of the pedostructure micro and macro pore water contents at equilibrium were derived such that

$$W_{ma}^{eq}(W) = \frac{\left(W + \frac{\bar{E}}{A}\right) + \sqrt{\left[\left(W + \frac{\bar{E}}{A}\right)^2 - \left(4\frac{\bar{E}ma}{A}W\right)\right]}}{2}, \quad (2a)$$

and

$$W_{mi}^{eq}(W) = W - W_{ma}^{eq} = \frac{\left(W - \frac{\bar{E}}{A}\right) - \sqrt{\left[\left(W + \frac{\bar{E}}{A}\right)^2 - \left(4\frac{\bar{E}ma}{A}W\right)\right]}}{2}. \quad (2b)$$

For equations 2a and 2b, A is a constant, such that $A = \frac{\bar{E}ma}{W_{maSat}} - \frac{\bar{E}mi}{W_{miSat}}$,

$\bar{E} = \bar{E}_{mi} + \bar{E}_{ma}$, and W_{miSat} and W_{maSat} are the micro and macro water content at saturation such that $W_{Sat} = W_{miSat} + W_{maSat}$.

Finally, the soil shrinkage curve of the pedostructure was derived such that

$$\bar{V} = \bar{V}_0 + K_{bs}w_{bs}^{eq} + K_{st}w_{st}^{eq} + K_{ip}w_{ip}, \quad (3)$$

where K_{bs} , K_{st} , and K_{ip} are the slopes at inflection points of the measured shrinkage curve at the basic, structural, and interpedal linear shrinkage phases, respectively [$\text{dm}^3 \text{kg}_{\text{water}}^{-1}$], and w_{bs} , w_{st} , and w_{ip} are the water pools associated to the linear shrinkage phases of the pedostructure in [$\text{kg}_{\text{water}} \text{kg}_{\text{soil}}^{-1}$] (Fig. 2). \bar{V} is the specific volume of the pedostructure [$\text{dm}^3 \text{kg}_{\text{soil}}^{-1}$], and \bar{V}_0 is the specific volume of the pedostructure at the end of the residual phase [$\text{dm}^3 \text{kg}_{\text{soil}}^{-1}$].

Thermodynamic characterization of the pedostructure allows for the definition of the micropore and macropore systems for every soil sample. Figure 3 illustrates the ShC with the partitioned soil structure between the micro- and macropore regions. Point M on the ShC in figure 3 approximates the point between the micro- and macropores spaces. Table 4 compiles these hydrostructural parameters used in this study. W_{mi} represents the amount of water that can be held within the primary peds and is considered the “main reservoir” in the soil medium (Assi et. al., 2017). W_{ma} represents the amount of water that can be held between the primary peds and

also represents the infiltration capacity of the soil, which is easily removed by gravity and evaporative forces. W_{sat} represents the water content in the soil at full saturation and is the sum of W_{ma} and W_{mi} . W_{sat} is calculated as the mass of the soil at saturation minus the mass of the soil after drying at 105°C for 48 hrs. This parameter is particularly useful for hydrologists and those interested in solute transport through the soil medium.

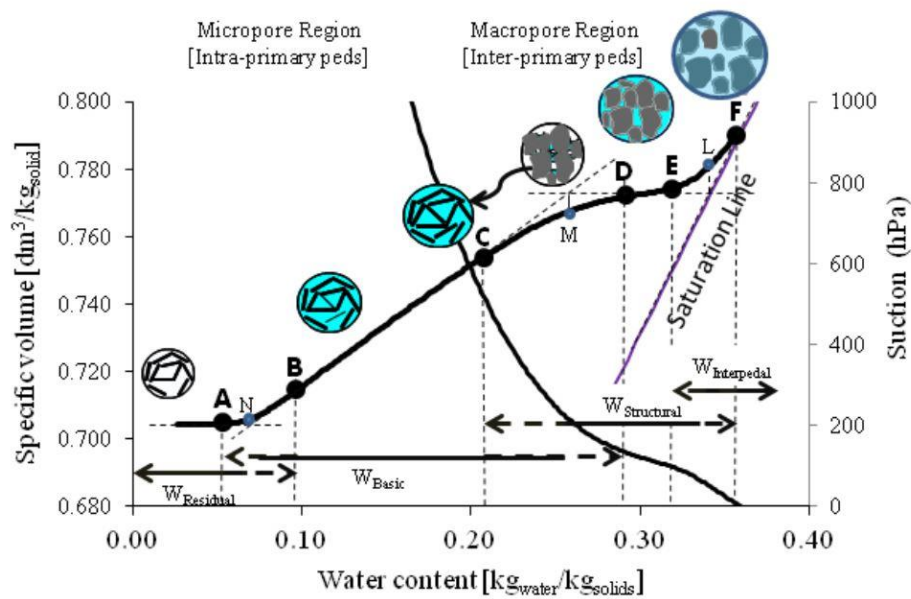


Figure 3: Arrangements of air and water apportioning into two pore systems. The two systems are the micro- and macropores, as related to the shrinkage phases. This figure has been adapted with permission from Assi et al. (2014).

Table 4: Summary of the characteristic parameters for soil water retention curve and shrinkage. These were utilized to evaluate treated wastewater irrigation effects on water holding properties.

Parameter	Unit	Description
W_{Sat}	kg _w /kg _s	Represents the water content in whole domain of soil at saturation.
W_{mi}	kg _w /kg _s	Represents the water content of the micropore volume at saturation. Thus, it is a <i>characteristic transition point</i> .
W_{ma}	kg _w /kg _s	Represents the water content of the macropore volume at saturation. Thus, it is a <i>characteristic transition point</i> .

The TypoSoilTM device was used to measure continuously and simultaneously the WRC and ShC with groups of eight unconfined cylindrical soil cores (100 cm³) through one drying cycle according to the method established by Assi et al. (2014). The TypoSoilTM consists of four main components: a biological stove that works at a fixed temperature (40°C for this study), an electronic analytical balance with MonoBloc weighting cell with a connection point's plate fixed upon it (used to close the electrical circuit to measure and record data), laser sensors - one spot laser (10 μm resolution) to measure height from the top and two thru-beam lasers (5 μm resolution) to measure the diameter of the soil core, and finally, a turning plate that houses 8 cylindrical soil samples at one time, which are placed on perforated support platforms. The support platforms contain a pressure gauge and a tensiometer operating at a functional range of 0 to 700 hPa and is in contact with the connection points on the balance to record the measured data. Once the testing in this device was completed, each soil sample was placed in an oven to dry at 105°C for 48 hrs, and the dry weights of each sample was recorded for the data analysis. Figure 4 shows the inside the TypoSoilTM with the samples inside the stove.

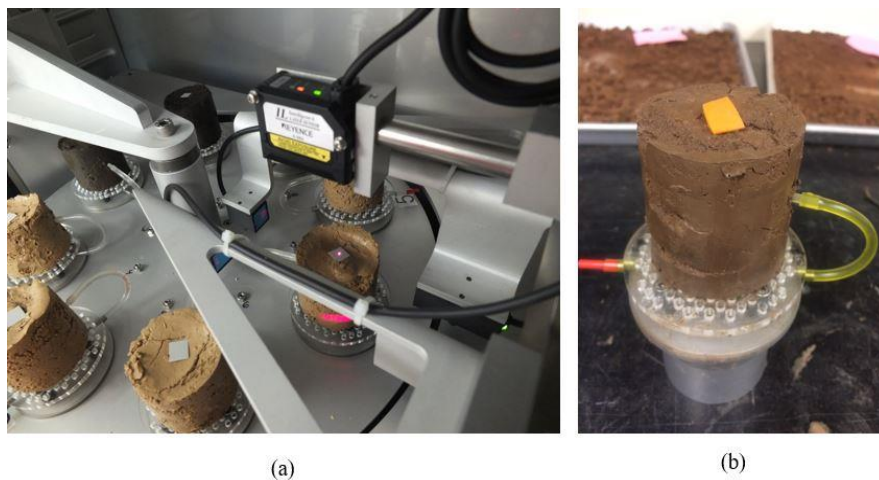


Figure 4: (a) Inside of TypoSoilTM device (TypoSoilTM User Manual),
(b) Standard soil core ($\phi = 5\text{cm}$, $h = 5\text{cm} \sim 100\text{cm}^3$)

The continuous measurement of the ShC and WRC allows for the identification and visualization of precise transition points and slope-portions of the curves that can be used to predict the soil moisture characteristic functions. Once the data was extracted, it was then analyzed to make an estimation of the pedostructure characteristic parameters (or hydrostructural parameters). The procedure for extracting and estimating the hydro-structural parameters involves the equations for the WRC and ShC defined previously. Extracting and estimating the hydro-structural parameters of the WRC and SSC involved the following steps: (i) identify the type of shrinkage curve, (ii) extract and/or give initial estimates of the values of the WRC parameters (W_{miSat} , W_{maSat} , E_{mi} , E_{ma}), (iii) minimize the sum of square errors between modeled and measured WRC by using the Microsoft Excel solver, (iv) extract and/or give initial estimates of the values of ShC parameters, and (v) minimize the sum of square errors between modeled and measured ShC by using the Microsoft Excel solver (Assi et al., 2014).

Quantification of Water Holding Parameters by Application of the Pedostructure Concept

This study is conducted in accordance with the Pedostructure Concept and Hydrostructural Pedology (Braudeau et. al. 2016) to apply a methodology of quantifying field capacity, permanent wilting point, and available water capacity as described and confirmed by Assi et al. (2017). Field capacity is traditionally defined by Veihmeyer and Hendrickson (1931) as the “amount of water held in soil after excess water has drained away and the rate of downward movement has materially decreased.” This concept is useful to determine plant available water and irrigation scheduling. The approach (Assi et. al., 2017) considers the unique structure of the soil medium which regulates water and nutrient circulation.

Thus, the methods for determining field capacity, permanent wilting point, and available water as established by Assi et al. (2017) are as follows:

Field Capacity (FC)

This paper operates under the definition of FC as the “water content at which the thermodynamic forces between soil and water are much higher than the gravitational forces to a point where the water flux out of soil medium is negligible” (Assi et al., 2017). This point can be identified by the quick change in the micropore water content curve. Thus, FC occurs at the point of maximum slope change in the W_{mi} curve, which can be seen in Figure 5. This point is found by calculating the point at which the third derivative of W_{mi} is zero, or where the second derivative reaches a maximum of absolute value. Figure 6 illustrates this second derivative of the W_{mi} curve at each water content point.

Permanent Wilting Point (PWP)

There is a transition point between the basic and residual shrinkage phases (point B in Figure 3), which Braudeau et al., (2004) defines as the “air entry point into the soil clayey plasma,” which builds upon the basic concepts used for the distinction of the primary peds structure level (Groenevelt and Bolt, 1972; Sposito, 1973; Sposito and Giraldez, 1976). At this point a capillary break in the microporosity of the primary peds occurs, and the plant roots can no longer reach the plant roots. Point B in figure 3 is at a soil suction 3791 hPa, which is equivalent to 15,000 hPa air pressure in a pressure plate, as proven by Braudeau et al. (2014b). This point can be calculated as the point of maximum change in slope (maximum absolute value of the second derivative) of the residual water content curve, W_{re} , as shown in Figure 5, and a change in slope curve for W_{re} is illustrated in Figure 6.

Available Water Capacity (AW)

Available water capacity is the difference between FC and PWP, such that

$$AW = W_{FC} - W_{PWP}. \quad (4)$$

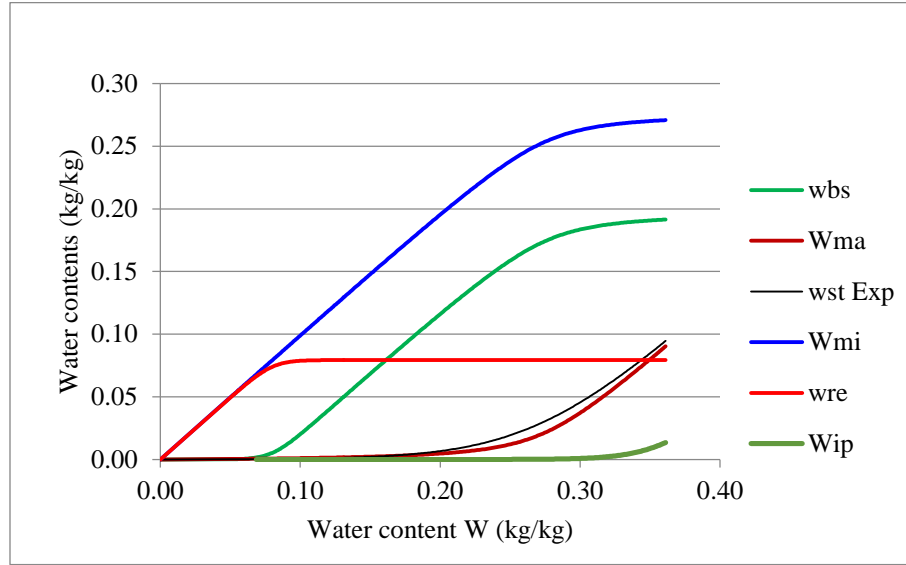


Figure 5: Modeling the pedostructure water contents from saturation to dry states. This allows for identifying the water content contributions of different water pore systems within the soil pedostructure, corresponding with the change in slope curves in Figure 6.

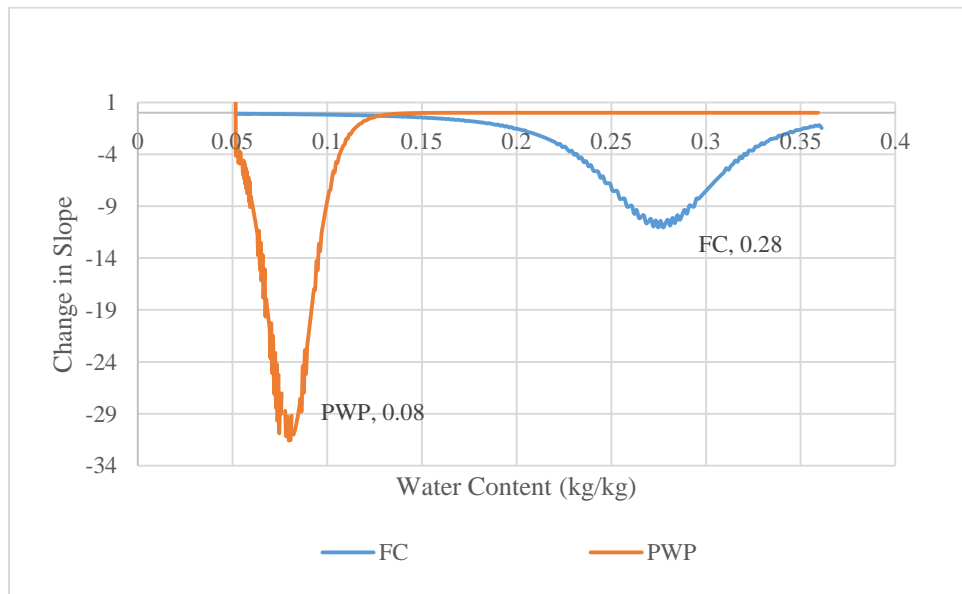


Figure 6: The value of field capacity and permanent wilting point. Field capacity calculation is based on maximum change in slope of pedostructure micropore water content curve, and the permanent wilting point based on the maximum change in slope in the pedostructure residual water curve, corresponding with Figure 5.

Characterization of Soil Chemical and Physical Properties

The particle size distribution of the soil samples was determined by the Hydrometer Method as defined by Bouyoucos (1962) and wet sieving. Cation Exchange Capacity (CEC) was determined using potassium saturation. Exchangeable bases (Ca, Mg, and Na) were determined by NH₄OAc extraction. Base saturation was then calculated as a percentage of the combined Ca²⁺, Mg²⁺, and K⁺ bases divided by CEC, times 100. Inorganic carbon content was obtained using the acid neutralization method, and organic carbon was obtained by the loss on ignition method. Electrical Conductivity (EC), soluble cations, and pH determined by a saturated paste. Exchangeable Sodium Percentage (ESP), Exchangeable Sodium Ratio (ESR), and Sodium Adsorption Ratio (SAR) were calculated by equations 5, 6, and 7, respectively.

$$ESP = 100 * \frac{[Na^+]}{[Ca^{2+}] + [Mg^{2+}] + [Na^+] + [K^+]} \quad (5)$$

$$ESR = 100 * \frac{[Na^+]}{[Ca^{2+}] + [Mg^{2+}]} \quad (6)$$

$$SAR = 100 * \frac{[Na^+]}{\sqrt{\frac{[Ca^{2+}] + [Mg^{2+}]}{2}}} \quad (7)$$

Statistical Analysis

This study applies statistical hypothesis t-test for a difference in means, with unknown variances. The null hypothesis, H₀ was treated as $\mu_1 - \mu_2 = 0$, where μ_1 and μ_2 are means for the measured values in each experimental group. The alternative hypothesis H_a was treated as $\mu_1 - \mu_2 \neq 0$ at a confidence of 95% ($\alpha = 0.05$). Each experimental mean came from 6 samples (n = 6, 3 samples from two locations) RF, TWW, and GW soil for three depth horizons. FF samples were only taken once from the top horizon (n = 3). This test was applied in the Microsoft Excel Data Analysis function.

3. RESULTS AND DISCUSSION

Soil Laboratory Testing

Results for the soil laboratory tests are compiled in Table 6 below.

Particle Size Distribution/Texture

A hydrometer test was conducted with replicate tests to determine the particle size distribution (PSD) or texture of the soil horizons. Clay contents were very high, and the results are similar to what is reported by the USDA-NRCS taxonomic classification, except these results report higher clay contents, especially in the treated wastewater irrigated soils. Further, it was found by a dropping a 10% HCl solution on the soil that all samples experienced moderate to strong effervescence, indicating the presence of calcium carbonates, which is to be expected in a limestone derived soil such as this.

pH

All pH values recorded are all slightly basic, but still within the acceptable range for cotton growth, which is 5.8 to 8.0; although, the optimum pH range for cotton growth is 5.8-6.5 (Faircloth, 2007). It does not seem that TWW irrigation has any notable effect on the pH of the soil in the top horizon, which is a finding consistent with Hidri et al. (2014) and Bardhan et al. (2016). However, in the A and B horizons, the pH is slightly higher in TWW soil than RF or GW. This could be due to an increase of cations like Na, Ca, and Mg, as hypothesized by Gwenzi and Munondo (2008) and Tarchouna et al. (2010).

CEC/Exchangeable Bases

The results of the tests for CEC and exchangeable bases confirmed a high Calcium presence in the soil, which was expected due to its limestone parent material. This is further confirmed by a very high base saturation percentage for all treatment types and horizons.

Salinity/Sodicity

As reported in the introduction, previous research shows an abundance of evidence that TWW irrigation increases the salinity and sodicity levels of soils. Recall that the TWW salinity verged upon very limiting at a value off 2.14 dS m^{-1} , but with an acceptable value of sodicity ($\text{SAR} = 4.7$) Also recall the GW water quality, that it reported very limiting salinity values ($\text{EC} = 7.02 \text{ dS m}^{-1}$; $\text{TDS} = 4312 \text{ ppm CaCO}_3$), but an acceptable sodicity ($\text{SAR} = 4.2$). The groundwater quality also recorded a very high presence of calcium, which can be attributed to the limestone formation of the aquifer from which it is drawn.

The test for EC imposes an electric potential to determine a current that varies directly with concentration of dissolved salts, which can include calcium salts. Calcium is a divalent cation, which would tend to flocculate when it accumulates, as opposed to sodium, a monovalent cation, which disperses with accumulation. Results indicate an increased salinity from TWW and GW irrigation in all horizons. In the A and B horizons, the salinity of GW irrigation is higher than the salinity of TWW irrigated soil. In the A_p horizon, TWW and FF irrigated soils have a higher salinity than GW irrigated soils. In terms of sodicity, as indicated by SAR, ESR, and ESP, none of the values even approach a sodic value of 15% (Bohn et al., 1985), so the results indicate that TWW or GW irrigation is causing an accumulation of sodium in the soil.

Results from TypoSoil™ and Extraction of Water Holding Parameters

Results from the TypoSoil™ are compiled in Table 7, and they are illustrated graphically in Figure 7.

Ap Horizon

The results from the TypoSoil™ indicate no significant changes in the W_{sat} of the A_p horizon due to TWW, GW, or FF irrigation in the A_p horizon, but an increase in the W_{misat} in the TWW and FF irrigated soils. The filter flush samples were only taken for the A_p horizon to see if there has been an accelerated effect from TWW irrigation with the concentrated suspended solids that will be in the water due to the backwash of the disk filter. The specific volume at field capacity (V_{FC}) will be utilized later in the discussion, so it is included in the hydrostructural properties table.

The water holding properties indicate that TWW irrigation causes a significant increase of the FC for the A_p horizon as compared with the rainfed and GW treatments, which would be a consistent finding with Tunc and Sahin (2015). This finding is further confirmed by an even higher increase of field capacity with the FF irrigation, which represents a form of the TWW with more suspended solids. This finding supports the conclusion drawn by Tarchitzky et al. (1999) that an increase in accumulation of organic matter from TWW irrigation causes an increase in water retention. This is supported by a significant increase in total organic carbon for FF, as can be seen in Table 6, but no increase in TOC is seen in the normal TWW A_p soil. Permanent wilting point was found to be significantly increased by TWW irrigation as compared with rainfed and GW irrigation as well. Overall, the available water capacity of the soil was not found to be significantly affected between TWW and RF treatments, but GW irrigated available water was found to be significantly lower than that of TWW irrigated soils. However, it is

important to remember that the drip tape is installed around 30 cm deep, so the A_p horizon does not experience as much TWW contact as the A and B horizons. The FF soil is flooded from the surface from a pipe every time the filter system back flushes, so it does experience full contact with the TWW. It is also important to note that the A_p horizon experiences significant disturbance from disk harrow tillage, so the soil is not well structured.

Thus, we will consider the A and B horizons more highly as indicators of the effect of TWW irrigation on soil since they experience full contact with the water and are well-structured.

A Horizon

Parameters extracted from the TypoSoilTM indicate that W_{sat} and W_{misat} had no significant changes with TWW or GW irrigation in the A horizon. Regarding the water holding properties, there is a downward trend in the A horizon for both FC and AW from RF to TWW to GW irrigation. However, these changes were found to be non-significant according to a 95% confidence. Additionally, changes in the PWP and AW between all irrigation treatments were also found to be non-significant.

B Horizon

Results from the TypoSoilTM indicate no significant changes in W_{sat} or W_{misat} for both TWW and GW irrigation in the B horizon. The trends for changes in water holding properties for the B horizon are very similar to that of the A horizon: a decrease in FC between RF and both TWW and GW; however, these changes were found to be non-significant. A significant change was found in the PWP, increasing from RF to TWW. No significant changes were found with the AW either.

Discussion of Impact on Parameters: Field Capacity, Permanent Wilting Point, and Available Water Capacity

In the top horizon A_p (0-15 cm), the most significant results were a clear increase in both FC and PWP due to TWW and FF treatments. However, this change did not cause a significant change in available water between TWW treatment and rainfed conditions, but there was a significant increase in available water content with TWW treatment as compared with GW irrigation. This could be due to an accumulation of organic matter in a disturbed soil (tillage), which adds water retention ability, as proposed by Tarchitzky et al. (1999), which is indicated in the TOC results for the FF soil, but not the TWW. Overall, the results for the A_p horizon indicate that for the initial stages of crop growth TWW irrigation is a suitable alternative to GW irrigation.

In the middle horizon, A (15-30cm), TWW and GW irrigation resulted in a slight (non-significant) decrease in FC and a significant increase in PWP for both. TWW did produce a significant decrease in AW, where GW did not, due to the variability of its numbers, even though its overall average is less than AW for TWW irrigation. GW irrigation also resulted in more of a decrease in field capacity and AW (but still non-significant) and also with a significant increase in PWP.

In the lowest horizon, B (30-72cm), TWW irrigation produced similar results as the previous A horizon for FC, PWP, and AW. The main difference is that for the B horizon, the resulting FC and AW for both TWW and GW treatments was almost the same, and the available water was significantly decreased for both treatments as well.

The decrease in FC and AW for the A and B horizons could be a result of flocculation resulting from the salinity of the irrigation waters, which could increase aggregate stability of

soil peds with decreased infiltration, as found by Vogeler (2009), Tunc and Sahin (2015), and Gharaibeh et al. (2016). Thus, overall, TWW irrigation did cause a slight reduction of the soil's ability to hold water in these deep root zone soil layers, but not more so than the GW treatment, indicating that, while RF soil is the healthiest soil in terms of water holding capacity, TWW is a suitable alternative to brackish GW for irrigation.

Table 5: Chemical and texture test results (RF = rainfed, TWW = treated wastewater, and GW = groundwater).

Irrigation Type	Clay Content	Texture	pH	Total Organic Carbon	Electric Conductivity	Sodium Adsorption Ratio	Cation Exchange Capacity	Na	K	Ca	Mg	Exch. Sodium Ratio	Exch. Sodium Percentage	Na	K	Ca	Mg
	%			%													
RF A_p (0-15 cm)	47.17	Clay	7.52	2.09	0.8	0.3	48	0.3	1.6	47.7	1.1	0.7	0.7	0.5	1.2	6.6	1.2
TWW A_p	50.9	Clay	7.61	2.09	3.6	1.5	46	0.6	2.1	41.6	3.3	1.2	1.2	6	4.9	22.8	9.9
GW A_p	54.51	Clay	7.66	2.27	1.6	0.6	59	0.5	1.9	45.6	2.4	1	0.8	1.5	0.9	11.2	2.3
FF A_p	50.9	Clay	7.46	2.54	3.5	4.6	51	1.9	1.3	39.9	4.7		3.7	12.8	1.9	11.6	4.2
RF A (15-30 cm)	33.4	Clay Loam	7.52	2.11	0.8	0.4	52	0.4	1.2	49.1	1	0.7	0.7	0.7	3.2	6.1	1.1
TWW A	42.92	Clay	7.41	1.84	1	1.5	47	0.6	1.5	42.4	3.4	1.4	1.4	2.9	1.2	5.4	2.2
GW A	49.68	Clay	7.17	2.28	2	0.1	36	0.6	1.2	44.7	2.1	1.2	1.6	0.3	1.2	13.8	2.6
RF B (30-72 cm)	35.26	Clay Loam	7.59	2.08	1	1.3	48	0.7	0.8	47	1.2	1.4	1.4	2.4	0.9	6.2	1.2
TWW B	45.31	Clay	7.38	1.74	1.2	3.4	47	1.3	0.8	42.2	3.8	2.7	2.7	5.9	0.6	4.1	2
GW B	49.52	Clay	7.33	2.22	2.8	3.4	50	1.5	0.7	43.2	3.4	3.2	3	10.6	0.7	14.4	5.1

Table 6: Hydrostructural and water retention results, extracted from the TypoSoil™.

Horizon	A _p				A			B		
	Rainfed	Treated Wastewater	Filter Flush	Ground-water	Rainfed	Treated Wastewater	Ground-water	Rainfed	Treated Wastewater	Ground-water
W_{sat} (kg_w/kg_s)	0.39 ± 0.02	0.39 ± 0.00	0.38 ± 0.02	0.38 ± 0.03	0.33 ± 0.04	0.31 ± 0.03	0.32 ± 0.02	0.34 ± 0.05	0.31 ± 0.03	0.32 ± 0.01
W_{missat} (kg_w/kg_s)	0.23 ± 0.04	0.29 ± 0.02	0.32 ± 0.03	0.25 ± 0.01	0.26 ± 0.03	0.25 ± 0.02	0.25 ± 0.03	0.27 ± 0.04	0.25 ± 0.02	0.24 ± 0.02
V_{FC} (dm³/kg_s)	0.84 ± 0.05	0.76 ± 0.03	0.73 ± 0.03	0.83 ± 0.06	0.70 ± 0.05	0.65 ± 0.03	0.70 ± 0.04	0.71 ± 0.09	0.61 ± 0.03	0.70 ± 0.08
Field Capacity (kg_w/kg_s)	0.23 ± 0.04	0.30 ± 0.02	0.33 ± 0.03	0.21 ± 0.04	0.27 ± 0.03	0.25 ± 0.02	0.23 ± 0.04	0.28 ± 0.05	0.25 ± 0.04	0.25 ± 0.02
Permanent Wilting Point (kg_w/kg_s)	0.05 ± 0.01	0.08 ± 0.01	0.07 ± 0.01	0.06 ± 0.01	0.06 ± 0.01	0.08 ± 0.01	0.07 ± 0.00	0.06 ± 0.01	0.07 ± 0.01	0.07 ± 0.00
Available Water Capacity (kg_w/kg_s)	0.18 ± 0.05	0.22 ± 0.02	0.25 ± 0.04	0.15 ± 0.04	0.21 ± 0.03	0.17 ± 0.02	0.16 ± 0.04	0.22 ± 0.05	0.18 ± 0.05	0.18 ± 0.02

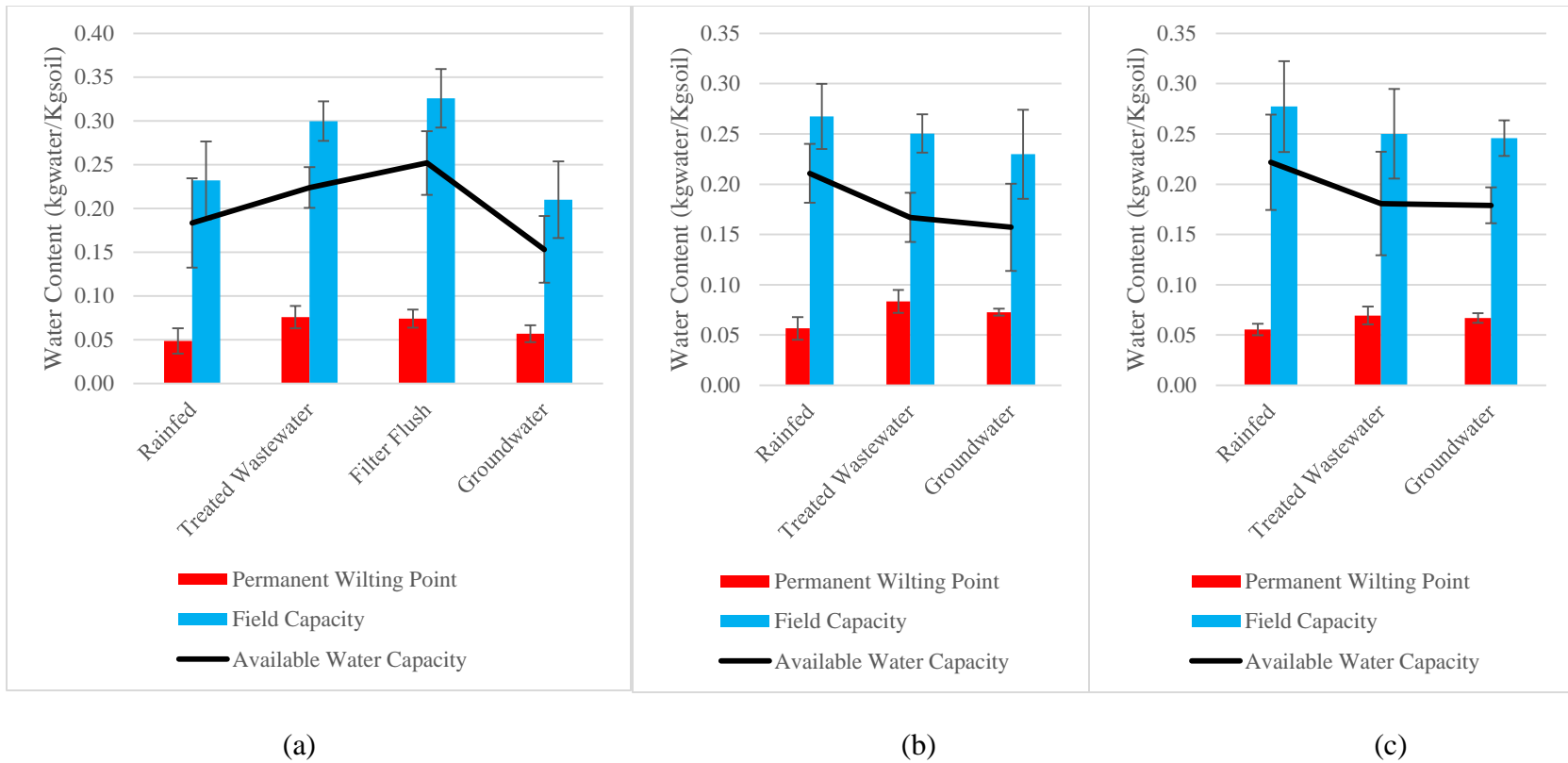


Figure 7: Results for field capacity, permanent wilting point, and available water capacity. Each horizon is such that (a) A_p horizon = 0 to 15 cm, (b) A horizon = 15 to 30 cm, and (c) B horizon = 30 to 72 cm.

Discussion of Impacts on Water Use

Extrapolation to Field-scale and Impact on Water Use

In terms of yield, the farmer at this study site prefers to use the TWW as irrigation over the brackish groundwater. He reports that typical average yield for each treatment is as follows: 0.75 bales/acre (1.85 bales/hectare) for rainfed fields; 3 bales/acre (7.41 bales/hectare) for GW irrigated plots; and 3.5 bales/ac (8.65 bales/hectare) for TWW irrigated fields (Figure 8a). Water holding capacity values indicate that TWW irrigation does not significantly decrease the water holding potential in any of the horizons *any more than GW irrigation*. Field capacity is increased in the top horizon with TWW irrigation, which confirms the same result as Tunc and Sahin, (2015) but with an unchanged available water capacity. Reasons for this increase, as mentioned it could be due to an accumulation of organic matter without aggregated pore space to clog in the tilled surface horizon; however, the TOC test does not confirm this hypothesis for the TWW treatment, but it does for the FF treatment, which presumably contains most of the suspended solids of the TWW filtered out by disk filtration.

Available water capacity in the soil affect irrigation frequency, as it will impact the amount of water held in the soil, which the farmer can account for when utilizing the water balance approach to irrigation scheduling (Andales et. al., 2015). An increased AW value would decrease the soil water deficit, causing less irrigation water to be necessary in each application, and vice versa. The available water content for the A_p horizon was not significantly impacted by TWW irrigation or GW irrigation compared to dryland conditions. Available water capacity in the GW irrigated A_p horizon was significantly less than available water in the TWW treatment. In the deeper A and B horizons, the TWW irrigation had the opposite effect: it decreased field capacity (non-significantly) and available water capacity (significantly) and increased the

permanent wilting point (significantly) as compared to rainfed conditions. This trend is also seen with the GW irrigation, with the exception of a non-significant decrease in available water for the A horizon. Thus, TWW and GW in this study both reduce the soil's ability to hold water for plants in the deeper horizons, which experience the most contact with the waters. ‘

Considering that TWW irrigation produces more yield per acre as compared to the much lower yields for both rainfed and GW treatment it becomes necessary to compare overall water availability to the plant and use per unit of cotton produce. Equation 8 was applied to convert the available water capacity (W_{AW}) into available water volume per acre for each horizon (AW_{irr}). Then, AW_{irr} was divided by the yield in terms of bales/acre to determine how much water is used per unit of cotton produced. The results of these calculations are displayed in Figure 8b.

$$AW_{irr} = \frac{W_{AW} * \rho_w * d_r}{V_{FC}}, \quad (8)$$

where,

AW_{irr} = available water per irrigation application (m^3/ac)

W_{AW} = Available water content (kg_w/kg_s)

V_{FC} = specific volume at field capacity (m^3/kg_s)

ρ_w = density of water ($1000 kg_w/m^3$)

d_r = depth of soil horizon (m)

*requires a conversion from m^2 to ac by this relation: $4046.86 m^2 = 1 \text{ acre}$

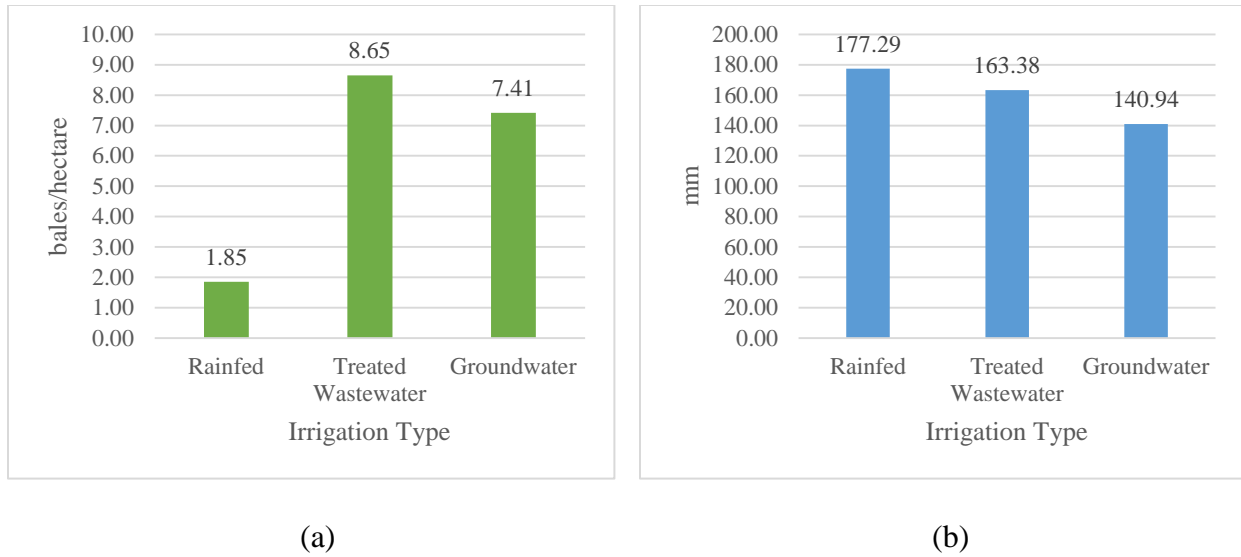


Figure 8: (a) Average yield per hectare. These values were reported by farmer Matthew Wilde. (b) Summed A, B horizon available water capacity. This is normalized to m^2 basis, calculated by Equation 8.

According to reported yield, it is clear that treated wastewater is producing the best results for the farmer, in terms of profitability. However, in terms of water holding capacity, the rainfed soil is the healthiest. Despite having the highest water holding capacity, though, the rainfed soil does not produce near the yields that treated wastewater and groundwater irrigated soils do because the rainfall conditions do not fill the “reservoir” in the soil enough for the cotton plant to thrive. Considering that the farmer need to irrigate for his operations to be profitable, the treated wastewater proves to be a suitable alternative to the groundwater as an irrigation source, since it does not degrade the soil’s ability to hold water any more than the groundwater.

Limitations

Analysis of the soil data is divided between three soil horizons: A_p (0-15 cm), A (15-30 cm), and B (30-72 cm). As reported earlier, the drip tape is installed around 30 cm deep into the soil profile, so tie TWW would presumably contact the A and B horizons first and more than the A_p horizon. Further, it is assumed that due to tillage practices, which extend 6-8 inches (15-20

cm) by disk turning, the top A_p horizon experiences significant disturbance in its hierarchical soil structure; whereas the deeper horizons, A and B, can be considered to have an undisturbed soil structure. Considering this and that samples were taken across times during the season non-uniformly (pre-sow, post-sow, and pre-harvest), it is important to note that there is a factor of unreliability of the quantities associated with the A_p horizon (0-15 cm), regarding hydrostructure. Also, considering that the root zone for a cotton plant can reach up to 90 cm, depending on conditions (Oosterhuis, D.M., 1990), the A and B horizon make up for the majority of the root zone depth in determining water holding capacities anyway. This study also only takes samples from one agricultural season, so it cannot be determined whether the changes found are continuing or have stabilized with regard to the effect of TWW and GW irrigation on soil water holding properties.

4. CONCLUSION

The future requires creative and localized solutions for human use of natural resources like water and soil and production of critical resources like food and energy. The city of San Angelo, Texas resides in a region with competition for water between the municipality and agriculture. To ameliorate this competition, the city discharges its secondary treated wastewater effluent for farmer irrigation use, and this study quantified and evaluated the effects of treated wastewater and brackish groundwater irrigation on the water holding ability of the soil compared to rainfed/dryland conditions. To recall the stated hypothesis: this study confirms that irrigating with TWW has decreased the ability of the soil to hold water available to plants. However, we build upon this hypothesis to consider the situation in San Angelo, Texas: irrigating with this municipal (secondary-level) treated wastewater source and quality (with an on-site disk filter) does not degrade the water holding capacity of the soil *any more than the available brackish groundwater available farmers*. The treated wastewater irrigated soil actually produces more yield and revenue of cotton for the farmer as compared to dryland conditions. Thus, irrigating with treated wastewater in this case is a suitable conservation practice, as the farmer is producing more cotton with this water, while drawing less groundwater from the underlying aquifer. It would be useful to conduct future research on the water-holding properties of this soil over subsequent time to determine whether they are continuing to degrade or if the effects of TWW and GW irrigation have stabilized, as compared to rainfed conditions. This information can be utilized by other areas which are considering reuse of TWW for crop irrigation, but it is important for these regions to understand the unique characteristics of their water sources and their soil, which will affect the soil's reaction to TWW irrigation.

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